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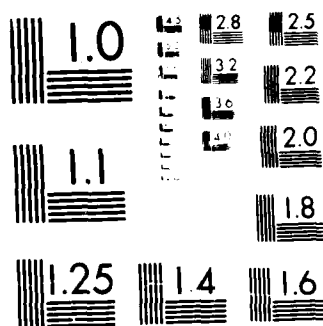
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Annual Report  
Contract No. AFOSR-86-0056  
November 15, 1985 - November 14, 1986

SIS MIXER RESEARCH

Submitted to:

Air Force Office of Scientific Research/PKD  
Building 410  
Bolling Air Force Base  
Washington, D.C. 20332-6448

Attention: Mr. Harold Weinstock

Submitted by:

M. J. Feldman  
Research Associate Professor

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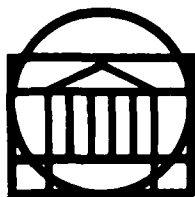
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March 1987



SCHOOL OF ENGINEERING AND  
APPLIED SCIENCE

DEPARTMENT OF ELECTRICAL ENGINEERING

UNIVERSITY OF VIRGINIA  
CHARLOTTESVILLE, VIRGINIA 22901

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19. ABSTRACT (Continue on reverse if necessary and identify by block number) <p>Theoretical and experimental research has been conducted to elucidate the basic physics behind the properties of superconductor-insulator-superconductor (SIS) tunnel junction receiving devices. The quantum theory of mixing was employed to calculate the saturation behavior of the SIS mixer and the SIS direct detector. The direct detector was found to saturate at far higher powers than previously believed, allowing the possibility of practical application of this device. Experiments verified the saturation theory. The mixer saturation expression led to the formulation of frequency scaling relations. The origin of quantum noise in the quantum theory of mixing was identified as the residual remaining when the usual noise sources are completely minimized. The mixer quantum noise limit was shown to be reached in only two special cases. Computer calculations determined that the behavior of SIS receivers divides into two regimes, low and high frequencies, the cross-over frequency depending upon junction quality. The properties of these two regimes were delineated.</p>												
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## 19. ABSTRACT (continued)

- All previous SIS receivers have operated in the low frequency regime. Plasma-etched niobium nitride edge junctions have been fabricated using a novel barrier formation process. These junctions have excellent current-voltage characteristics, but their precise physical nature has not yet been determined.

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## II. Research Objectives

The research objectives set forth in the proposal leading to this grant are the following:

1. The first objective of this research is to conduct a careful and exhaustive analytical examination of the quantum theory of mixing, in order to derive new general results from the theory and to clarify the behavior of SIS mixers.
2. The second objective of this research is to analyze the behavior of arrays of SIS junctions.
3. The third objective of this research is to study the limitations of SIS mixers at higher frequencies, close to and exceeding the energy gap frequency of the superconductors used.
4. The fourth objective of this research is to fabricate and evaluate plasma-etched NbN edge junctions to study the mechanisms of oxide growth on a shaped NbN surface.

## III. Status of the Research

**1. Quantum theory:** We employed the quantum theory of mixing to calculate the saturation properties of the SIS direct detector [Pub. 2]. Although early papers on SIS direct detection reported the highest sensitivities ever achieved for a direct microwave detector, this device has been completely ignored in the literature since 1981. One reason for this neglect has been the assumption, by us and by other researchers, that this device would saturate for unusably small signal powers. This reasonable assumption was based on an analogy with the severe saturation levels of the SIS mixer; the direct detector cannot resort to either of the techniques employed to avoid mixer saturation. However, our calculation shows that the SIS direct detector begins to saturate only at powers far larger than for a comparable SIS mixer. This result warrants a reconsideration of SIS junctions for direct detection of millimeter wavelength radiation, in competition with the helium-three-cooled bolometers now used.

We determined the complete expression for the responsivity of the SIS direct detector, including the lowest order terms dependent upon the incident signal power which cause the saturation. Assuming typical parameter values, we found that a thermal signal of temperature  $T$  and bandwidth  $\Delta\nu$  around frequency  $\nu$  will suppress the responsivity by less than 1% so long as  $T\Delta\nu/\nu \leq 600$ . This is roughly 200 times larger than the saturation power of a comparable SIS mixer. Experiments performed in conjunction with L.R. D'Addario of the National Radio Astronomy Observatory (NRAO) using  $N=2$  and 4 SIS junctions in series, qualitatively verify the saturation theory [4]. However, the measured detector responsivity is greater than the quantum limit  $e/N\hbar\omega$ . This is not understood. A careful analytical treatment of two non-identical series junctions shows that this discrepancy is much too large to be caused by differences between the junctions.

We also determined an explicit expression for the gain saturation of the SIS mixer [4]. Previous work had given only the approximate power at which saturation would occur. Our expression, assuming typical parameter values, implies that a thermal signal must obey  $T\Delta\nu/\nu \leq \nu/40$  GHz to avoid 1% gain suppression of a unity-gain single-junction SIS mixer. Thus room temperature radiation in a 1% bandwidth will saturate such a mixer at frequencies as high as 120 GHz. Our new result has already proven useful to designers of practical SIS receivers; to avoid saturation the mixer can either be narrow-banded or employ a series array of junctions. In conjunction with A.R. Kerr of NRAO we used the mixer saturation expression to formulate a set of frequency scaling relations for SIS mixers which maintain either the saturation power or temperature [7]. Given an SIS element optimized for one frequency band, these relations completely determine the optimum SIS element for a scaled mixer block at any other frequency, between 50 and 350 GHz.



We have investigated the origin and characteristics of quantum noise in the quantum theory of mixing [3]. The proposal underlying this grant stated that "This noise is not contained in (the) quantum theory ..." We now know that this statement is false. We have shown that the lowest possible equivalent input noise power of any device obeying the quantum theory of mixing in the three-port, low IF model, allowing arbitrary terminations at each frequency, is  $\hbar\omega/2$  per unit bandwidth. This means that no extraneous noise source need be postulated to produce the quantum noise, contrary to many papers written on the quantum theory of mixing. Instead, the quantum noise is the residual remaining when both of the obvious noise sources, thermal noise in the termination impedances and shot noise, are minimized, and it is generated by the combination of these two minimized noise sources. Other phase-preserving, high-photon-gain, linear amplifiers, such as the maser and the parametric amplifier, have the same minimum noise, and this is ultimately a consequence of the Heisenberg uncertainty principle.

In addition, we showed that the mixer quantum noise limit can be reached in only two special cases, approximated by the super-Schottky mixer in the limit of large local oscillator power, and by the SIS mixer in the limit of small power. For the ideal SIS mixer, the minimum noise is found for one particular value of source impedance, regardless of the value of the image termination impedance. This appears to violate the assumptions of the most widely quoted theory [C.M. Caves, Phys. Rev. D26, 1817 (1982)] of quantum noise in linear amplifiers.

**2. Arrays:** Little has been accomplished on this topic, but preparations are being made for future research. A new graduate student is doing background reading for this. Our time-domain SIS mixer analysis computer program, which uses the quantum theory of mixing in its most general formulation, has now been verified and documented [1] and should be useful for this project. SIS junctions suitable for examining array noise are now being fabricated (see Sec. 5).

**3. High frequency:** We have developed a new computer program, based on the quantum theory of mixing, which is capable of predicting the performance of SIS mixers both at low frequency, where the behavior is relatively familiar, and at high frequency, up to a few times the superconducting energy gap frequency. The program uses synthetic SIS junction I-V characteristics with variable parameters so that the behavior of a wide range of realistic SIS junctions can be simulated and their performance charted as a function of junction quality. We find [5, 10] that for a given SIS junction in an optimized (at each frequency) mixer mount, the receiver sensitivity should improve to higher frequency after leaving the classical limit until reaching some "best" frequency. Above that, the receiver noise should linearly increase with frequency staying at roughly 2-5 times the quantum limited noise temperature  $\hbar\omega/2k$  until nearly twice the energy gap frequency.

We distinguish between the "low" and "high" frequency regimes, as being respectively below and above that best frequency. The most important effect of junction quality is that the turn-around frequency is roughly proportional to the voltage width of the energy gap current rise in the junction I-V curve. Therefore, of course, junction quality is crucial in the low frequency regime. But contrary to general belief, junction quality is important even in the high frequency regime, in that a moderately good junction may give twice the receiver noise temperature as an excellent junction.

We find that SIS receiver behavior is qualitatively different in the two frequency regimes. For instance, at low frequency the noise temperature of an optimized receiver is strongly dominated by IF amplifier noise, whereas at high frequency the mixer noise is of comparable importance. Since all previous SIS receivers have operated in the low frequency regime, receiver design criteria are derived from experience in this region. But in the near future, with higher quality junctions and/or higher signal frequencies, many SIS receivers will operate in the unfamiliar high frequency regime.

This calculation confirms published predictions of near-quantum-limited sensitivity SIS receivers at frequencies up to twice the energy gap frequency, about 3 THz for high quality NbN SIS junctions under development. We have begun to investigate the numerous effects not included in the simple theory which may forestall this prediction [6].

**4. Plasma-etched NbN edge junctions:** Our procedure for fabricating these junctions is, in brief, to passivate the NbN film with sputtered  $\text{SiO}_2$ , to define by photolithography and then to cut an edge on the NbN in a parallel-plate plasma etcher using  $\text{CF}_4$  and  $\text{O}_2$ , to define by photolithography the counterelectrode area, to clean the NbN edge with an Ar plasma in a high vacuum system and then to reactively oxidize it by admitting  $\text{O}_2$  into the plasma, and finally to evaporate a PbBi counterelectrode, using photoresist liftoff to remove the excess. We soon found that we could make extremely high quality junctions, having very low leakage current and sharp current onset at the gap voltage, with no  $\text{SiO}_2$  passivation layer, if we omitted the plasma oxidation step altogether. The insulating barrier is apparently formed during the  $\text{CF}_4/\text{O}_2$  plasma edge cutting step; Auger Electron Spectroscopy determined that the barrier contains Nb, C,  $\text{O}_2$ , and F. Others have noted that the inclusion of F in  $\text{Nb}_2\text{O}_5$  yields a barrier almost free of deleterious suboxides. This novel barrier formation process yields NbN/PbBi edge junctions that have I-V curves (Fig. 1) of at least as high quality as similar planar junctions made elsewhere.

To optimize the shape of the NbN/ $\text{SiO}_2$  edge we have investigated using 1) a two-step wet chemical etch, 2) a two-step wet chemical etch followed by a plasma etch, and 3) a single-step  $\text{CF}_4/\text{O}_2$  plasma etch. The third technique appears superior at present, yielding a far more desirable edge profile and surface morphology under a scanning electron microscope. We intend to modify our high vacuum plasma system to handle  $\text{CF}_4$  so that the NbN edge may be oxidized in a  $\text{CF}_4/\text{Ar}/\text{O}_2$  plasma. An RIE system recently obtained for semiconductor research in our laboratory may also be useful in this work. This project now has our renewed attention after a change in personnel.

**5. Related research:** We have begun to fabricate Nb/ $\text{Al}_2\text{O}_3$ /Nb trilayer SIS junctions in our laboratory. A reliable source of refractory SIS junctions will directly benefit many aspects of the grant research. In addition, we are involved in several other projects [in part reflected in Pubs. 1, 8, 9] which may lead to significant advances in the grant research.

#### IV. Publications

1. R.G. Hicks, M.J. Feldman, and A.R. Kerr, "A general numerical analysis program for the superconducting quasiparticle mixer," NASA Technical Memorandum TM-86145 (National Aeronautics and Space Administration, Washington, D.C., July 1986).
2. M.J. Feldman, "Saturation of the superconductor quasiparticle direct radiation detector," J. Appl. Phys. 60, 2580-2582 (1 Oct. 1986).
3. M.J. Feldman, "Quantum noise in the quantum theory of mixing," IEEE Trans. Magnetics MAG-23, to be published.
4. M.J. Feldman and L.R. D'Addario, "Saturation of the SIS direct detector and the SIS mixer," IEEE Trans. Magnetics MAG-23, to be published.
5. C.K. Huang and M.J. Feldman, "High frequency performance of the superconductor quasiparticle mixer," Bull. Am. Phys. Soc. 32, 713 (1987).

6. M.J. Feldman, "Theoretical considerations for THz SIS mixers," in preparation, for special issue of Int. J. Infrared Millimeter Waves, Oct. 1987.
7. A.R. Kerr, M.J. Feldman, and S-K Pan, "SIS mixer design by frequency scaling," in preparation, probably for IEEE Trans. Microwave Theory Tech.
8. S-K Pan, A.R. Kerr, J.W. Lamb, and M.J. Feldman, "SIS mixers at 115 GHz using Nb/Al-Al<sub>2</sub>O<sub>3</sub>/Nb junctions," in preparation.
9. S-K Pan, A.R. Kerr, M.J. Feldman, A. Davidson, A. Kleinsasser, and J. Stasiak, "A broadband 90-120 GHz SIS mixer using inductively shunted edge-junctions," in preparation.
10. C.K. Huang and M.J. Feldman, "Frequency regimes of the superconductor quasiparticle mixer," in preparation.

#### **V. Professional Personnel under Research Grant**

Marc J. Feldman, Research Associate Professor  
 Robert J. Mattauch, Professor  
 Alan S. Lewis, graduate student  
 Chung-Ken Huang, graduate student  
 Steven W. Yates, graduate student, 2 months  
 Ricky S. Amos, graduate student

All personnel are members of the Department of Electrical Engineering of the University of Virginia.

A Masters of Science degree was awarded to Alan S. Lewis on November 21, 1986. His thesis was entitled "The Effect of Composition on the Superconducting Properties of Niobium Nitride and Niobium."

#### **VI. Interactions**

Marc J. Feldman participated in the following major interactions during the grant period:

1. Presented invited lecture "Quantum Detection of Millimeter Wavelengths" at Yale University, New Haven, Connecticut, November 15, 1985, followed by extensive discussions with Yale personnel on the fabrication and properties of SIS junctions.
2. Attended the March Meeting of the American Physical Society, March 31 - April 4, 1986, in Las Vegas, Nevada.
3. Presented two talks, "Quantum Noise in the Quantum Theory of Mixing," and "Saturation of the SIS Direct Detector and the SIS Mixer," at the 1986 Applied Superconductivity Conference, September 29 - October 3, in Baltimore, MD.
4. Presented invited lecture "Mixers, Local Oscillators, and Amplifiers" at the 1986 US-Japan Workshop on Josephson Junction Electronics, October 3-4, at the National Academy of Sciences, Washington, D.C.
5. Toured laboratories of P.L. Richards and W.C. Danchi and extensively discussed the properties of SIS mixers, at the University of California, Berkeley, California, in conjunction with attendance at an unrelated research conference, October 24-25, 1986.

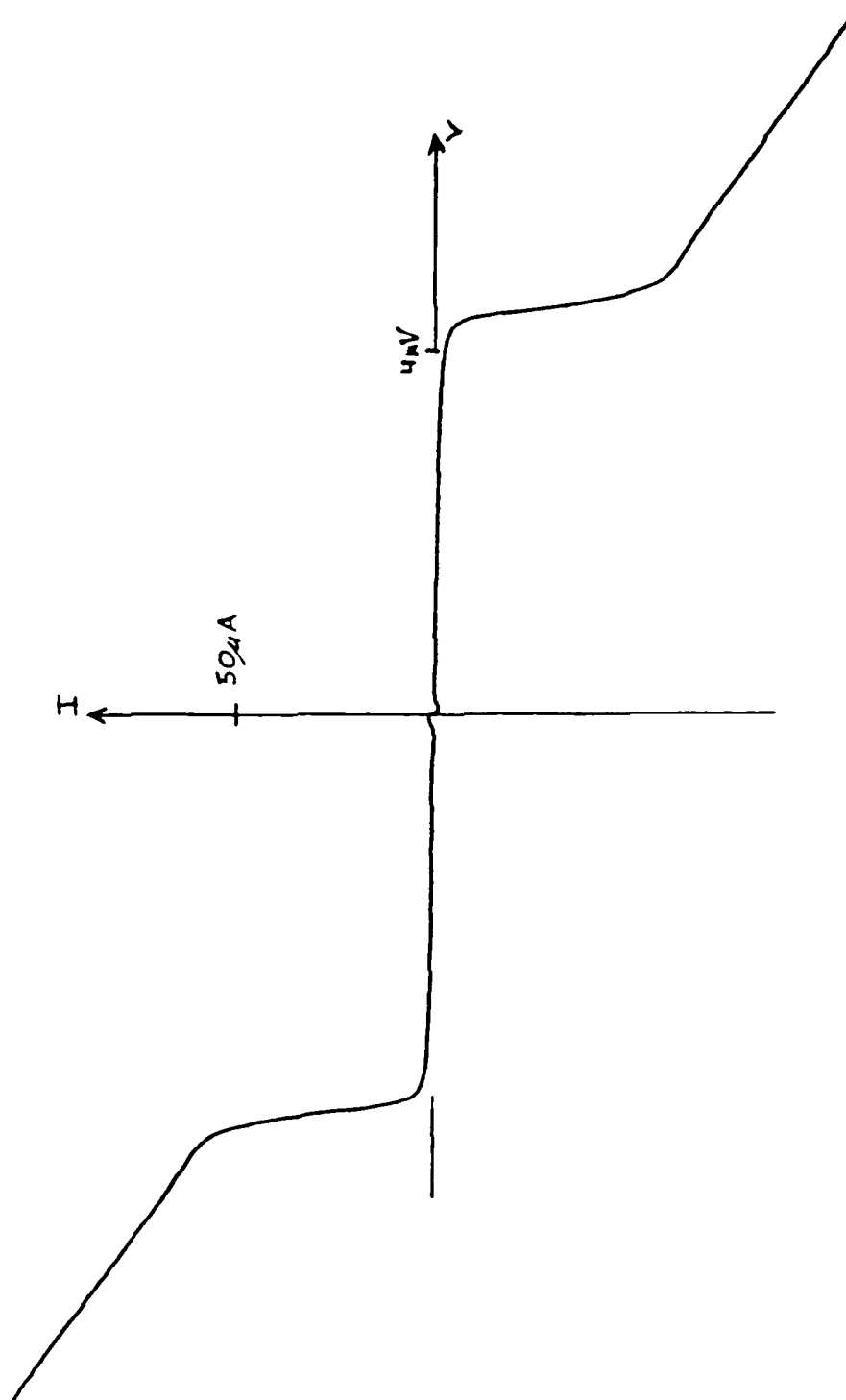


Figure 1. Current-voltage characteristic of a NbN/PbBi plasma-etched edge junction.

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**UNIVERSITY OF VIRGINIA**  
**School of Engineering and Applied Science**

The University of Virginia's School of Engineering and Applied Science has an undergraduate enrollment of approximately 1,500 students with a graduate enrollment of approximately 560. There are 150 faculty members, a majority of whom conduct research in addition to teaching.

Research is a vital part of the educational program and interests parallel academic specialties. These range from the classical engineering disciplines of Chemical, Civil, Electrical, and Mechanical and Aerospace to newer, more specialized fields of Biomedical Engineering, Systems Engineering, Materials Science, Nuclear Engineering and Engineering Physics, Applied Mathematics and Computer Science. Within these disciplines there are well equipped laboratories for conducting highly specialized research. All departments offer the doctorate; Biomedical and Materials Science grant only graduate degrees. In addition, courses in the humanities are offered within the School.

The University of Virginia (which includes approximately 2,000 faculty and a total of full-time student enrollment of about 16,400), also offers professional degrees under the schools of Architecture, Law, Medicine, Nursing, Commerce, Business Administration, and Education. In addition, the College of Arts and Sciences houses departments of Mathematics, Physics, Chemistry and others relevant to the engineering research program. The School of Engineering and Applied Science is an integral part of this University community which provides opportunities for interdisciplinary work in pursuit of the basic goals of education, research, and public service.

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